

2nd International Conference on Structural Integrity and Exhibition 2018

Structural integrity of ultrafine grain Al-3%Mg alloy under dynamic loading conditions

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Abstract

Utilization of various materials for constructing dynamic components and equipments has increased ever today. The high speed deformation mechanics was studied in various scale levels, especially in micro and nano scales. Understanding the micromechanics using shock waves led to development of armor plates in military technology. One dimensional elastic stress is applied using Split Hopkinson pressure bar for the ultra-fine grain aluminum samples and microstructural evolution was discussed in detail. The material characterization of equi channel pressing and its effect on stability of material after shock wave testing is provided. The grain size of material is steadily decreased to obtain ultra-fine grain structure during equi channel pressing and by application of shock waves on those pressed samples, the grain size again increases within the material. The recovery, re-crystallization and grain growth was observed in those shock tested samples due to induced temperature during such shock testing. The existing dislocation sub structure in pressed samples devoid after inertia effects. It is proposed further to understand the interaction between precipitate particle and dislocations.

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Selection and peer-review under responsibility of Peer-review under responsibility of the SICE 2018 organizers.

Keywords: Ultra-fine grain; Dynamic response; Material behaviour; Shear band deformation

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1. Introduction

The prediction of crashworthiness, earthquakes, space vehicle shielding, explosive welding and cutting, explosive interactions with materials, explosive forming, rock blasting, ordnance applications, perforation of oil wells and high velocity projectiles in defeat or collapse of opponent structures are characterized by dynamic behaviour of materials, components and structures. Sanan H Khan et al (2018) shows that the design, development and shielding to prevent high velocity damages require fundamental understanding of dynamic material behaviour, dynamic mechanics on continuum bodies and dynamic fracture mechanics. One such developed military application is armour which protects structures from high velocity projectiles. The material behaviour in dynamic loading conditions is extremely important in current industrial scenario. The impact like situation is to be evaluated for safe and efficient designs in auto and aerodynamic structural systems. The novel material developments like carbon nano tubes, ultra-fine grain materials, functionally graded composites, shape memory alloys and high entropy alloys with superior functional properties are used in variety of engineering applications. Due to high strength-to-weight ratio, aluminium alloys are extensively used in automobiles and aerospace structural applications. Govinda Krishnan et al (2017) shows that dynamic change effects the stress corrosion and mechanical cracking behaviour. Muhammad Jawad Qarni et al (2017) and S Giribaskar et al (2012) augmented that the ultrafine grain processed titanium and aluminium alloys have several advantages namely high strength to weight ratio, superior mechanical, corrosion, wear and other functional properties. The strain rate (s^{-1}) required for creep phenomena is between 10^{-6} to 10^{-8} , for quasi static 10^{-3} and for high strain rate testing is 10^3 and above within the materials. Yurii Meshcheryakov et al (2017) studied structural instability of aluminium alloys at high strain rate test conditions. The flow stress increases with increase in strain rate and decrease in temperature in many metallic materials. Ivan Smirnov et al (2017) shows that the mechanical properties improvement depends upon grain size, grain orientation, precipitate size, and interaction between precipitates and dislocation structures which plays a major role in correlating microstructure and property relationship. Svetlana Atroshenko et al (2017) and Zimin B.A et al (2016) clearly show that transient heat release during high strain rate dynamic material behavior. Such heat release is very high and in various steel grades this heat will result in formation of brittle martensitic phase structure and shear bands due to high velocity projectile. However, the effect of similar studies is limited for aluminum alloys. This paper discusses one such study in which grain was refined to improve material properties by equi channel pressing and subsequently tested at high strain rate testing conditions.

Nomenclature

U	axial displacement of a bar material
t	time
C_B	stress wave constant
E_B	elastic modulus of the bar material in which stress waves propagated
ρ_B	density of the bar material in which stress waves propagated
F_1	force at front end of test specimen
F_2	force at back end of test specimen
A_B	cross sectional area of the bar
ϵ_I	incident strain in test specimen
ϵ_R	reflected strain in test specimen
ϵ_T	transmitted strain in test specimen
T_m	melting temperature of test specimen

2. Experimental methods

The commercial Al-3%Mg alloy was subjected to Equi-Channel Angular Extrusion (ECAE) through route B_C up to four passes at room temperature. The sample was rotated at 90° between each subsequent passes in B_C route. The last pass (i.e. fourth pass) samples are subjected to high strain rate testing above $1000s^{-1}$ using Split Hopkinson

Pressure Bar (SHPB) technique for 150 μ s pulse duration by compressive stress (refer figure 1a), and the microstructural characterization was examined before and after dynamic testing. A rod sample of approximate diameter which equals to two times of length was subjected to in high strain rate testing. Thin ductile annealed copper disc sheet (refer figure 1b) was used in SHPB experimentation to control the loading pulse for obtaining an equilibrium at various interfaces of test bar during testing. Microstructural studies were conducted on ultra-fine grain processed samples before and after dynamic testing. Microstructural characterization was studied using transmission electron microscope FEI TECHNAI G2 20 U twin microscope model.

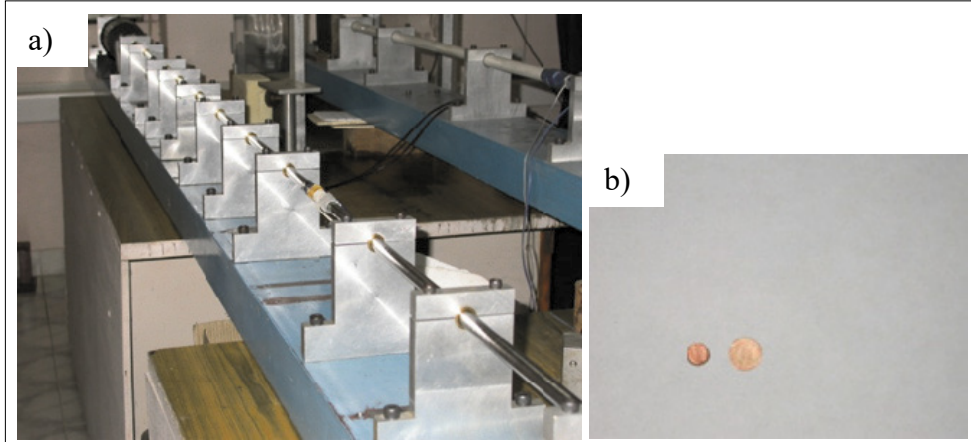


Fig. 1. (a) Split Hopkinson Pressure Bar experimental setup; (b) annealed copper sheets fixed on specimen face to form equilibrium loading pulse, former shows before deformation and later shows after deformation at strain rate above 1000s⁻¹.

3. Mechanics of deformation

The mechanics of deformation in Split Hopkinson pressure bar technique is fundamentally derived from wave propagation of slender rod as stated in equation 1 and elastic stress wave constant depends on material property of bar material as shown in equation 2.

$$\frac{\partial^2 U}{\partial x^2} = \frac{1}{C_B^2} \frac{\partial^2 U}{\partial t^2} \quad (1)$$

$$C_B = \sqrt{\frac{E_B}{\rho_B}} \quad (2)$$

The forces at two ends i.e. F_1 , F_2 of specimen is stated in equation 3 and equation 4, and during high velocity jet profile, the forces at these two ends of the specimen will be in equilibrium as stated in equation 5.

$$F_1 = A_B E_B (\epsilon_I + \epsilon_R) \quad (3)$$

$$F_2 = A_B E_B \epsilon_T \quad (4)$$

$$\epsilon_I + \epsilon_R = \epsilon_T \quad (5)$$

The pulse data acquisition from dynamic testing of equi-channel pressed Al-3%Mg ultra-fine grain alloy (four times pressed sample) is shown in figure 2. Both incident and reflected pulse data obtained from strain gauge fixed in incident bar, and transmitted pulse data was obtained from strain gauge fixed in transmitted bar.

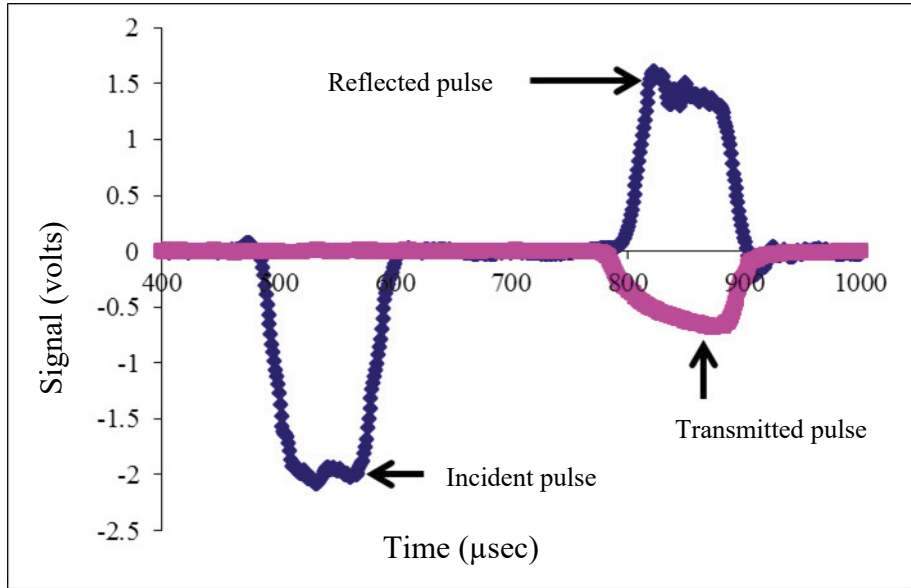


Fig. 2. Pulse data acquisition during Split Hopkinson pressure bar technique for ultra-fine grain Al-3%Mg alloy.

4. Results and discussions

4.1. Evolution of microstructure after equi-channel angular extrusion

The microstructure evolution of a sample was subjected to one, two, three and four passes of equi-channel angular extrusion as shown in figure 3, figure 4, figure 5 and figure 6 respectively. The dense dislocation structure clearly reveals typical cold work structure.

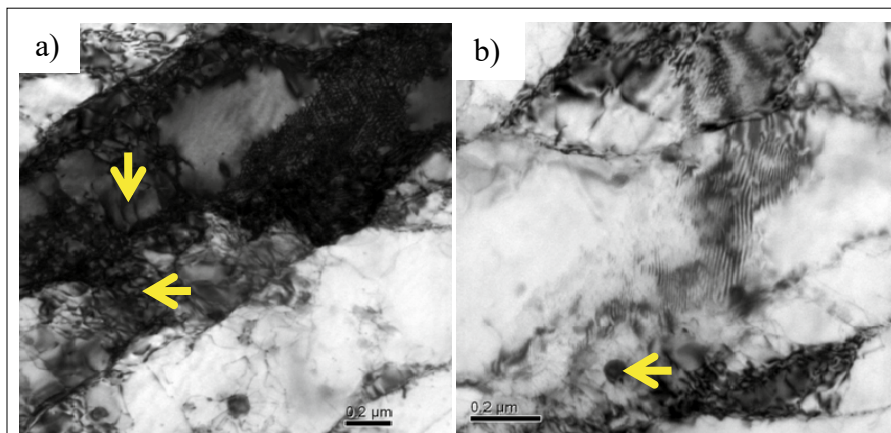


Fig. 3. (a) TEM micrograph a) and b) after first pass pressing, arrow shows dislocation structure and particle.

However after first pass, the grain structure is not uniform and reveals banded structure. The shear stress is responsible for material yielding in equi-channel angular extrusion process leading to accumulated shear strain within the material in its grain boundaries. Very high shear strain accumulation within grain boundary will result in formation of new grain boundaries called sub-structure cellular boundaries (refer figure 3a). An increase in strain

during each individual passes will increase the accumulated strain resulting in formation of large number of sub-grains and ultra-fine grains. The precipitates in the material are severely resistant to sub-structure dislocation movements and it also increases the strength of material (refer figure 3b). After second stage ECAE processing, the re-crystallized grains in ultra-fine range evolved as shown in the microstructure (refer arrows figure 4a and 4b). The increase in shear strain accumulation shifts the banded structure in first pass to equi axed morphology in second pass. An increase in re-crystallized grains appears after third pass of ECAE processing without large number of dislocations and dislocation cell structures (refer figure 5a). The recovery and re-crystallization within the material attributed to increase in number of re-crystallized grains. An interaction of precipitates with dislocation sub-structure is also observed after third pass (refer figure 5b) and still few lower dislocation densities were observed. The dynamic re-crystallized grains and larger extent dislocation free grains are observed after fourth stage of ECAE processing (refer figure 6a). An electron diffraction pattern was obtained within selected area aperture of 2μ which indicates numerous grains image in each pattern. The diffraction spot fairly reveals large number of grains in nano crystalline range of less than 100nm with almost continuous ring pattern (refer figure 6b).

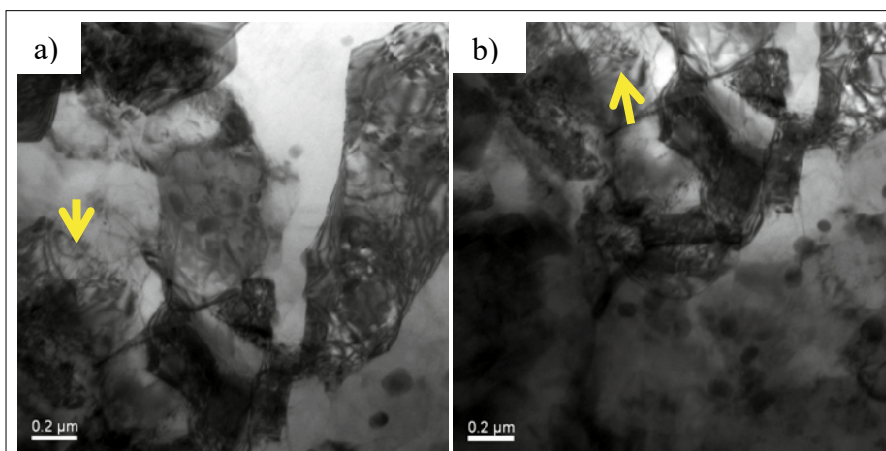


Fig. 4. (a) TEM micrograph a) and b) after second pass pressing.

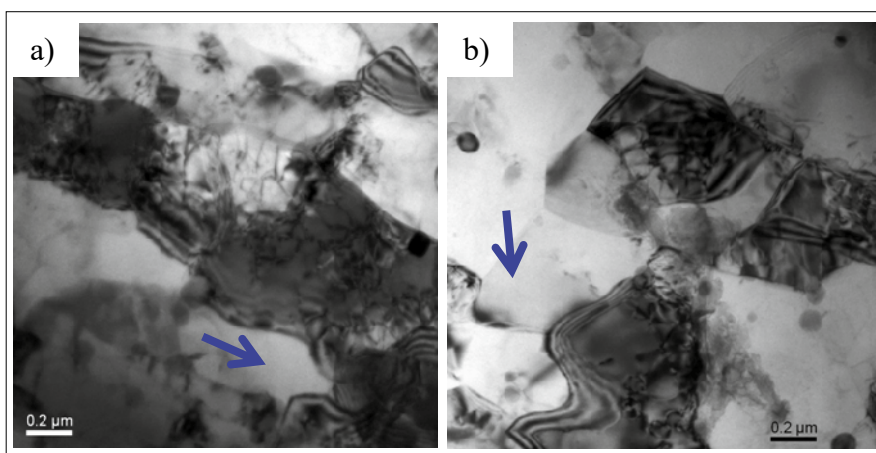


Fig. 5. (a) TEM micrograph a) and b) after third pass pressing.

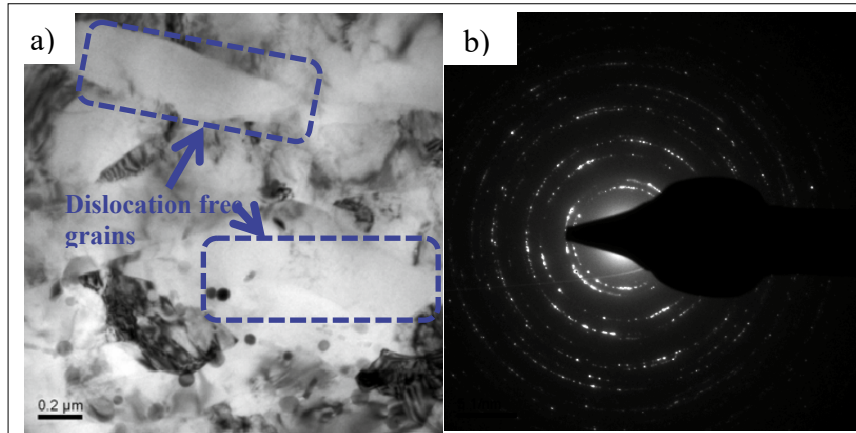


Fig. 6. (a) TEM micrograph after four pass pressing; b) its electron diffraction pattern image.

4.2. Characterization of dynamic response of material

The fourth pass ultra-fine grain material was tested under dynamic load of strain rate more than 1000s^{-1} and the sample was subjected to high plastic deformation similar to plastic crush in compressive deformation. After such conditions, the deformed sample reveals large fraction of equi-axed grain structure without dislocations or dislocation sub structures (refer figure 7a). The selected area diffraction pattern of dynamic loaded sample clearly reveals increase in grain size when compared to as-pressed conditions (figure 9b). It is inferred that during dynamic loading applications, the grains might have grown as result of high temperature experienced within the material. The dark field transmission electron micrograph reveals bright grains which confirms dynamic re-crystallization concurrently taking place along with plastic deformation (refer figure 7b). Once the strain attains critical strain, the new re-crystallized grain is nucleated within the deformed material as shown in figure 8a and 8b. The generation of new re-crystallized grains will be possible within the material only if it reaches or exceeds $0.4T_m$ temperature during adiabatic heating.

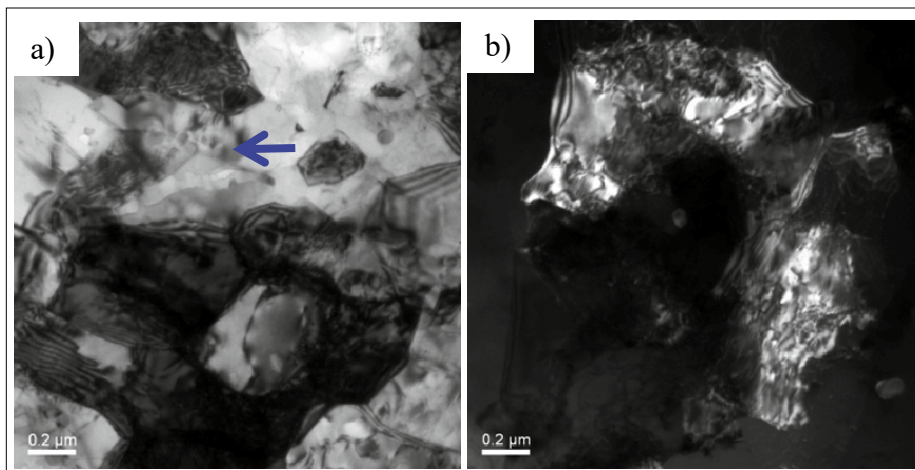


Fig. 7. (a) TEM micrograph of fourth pass sample after dynamic testing a) plane parallel to applied stress direction; b) dark field image in parallel to applied stress direction.

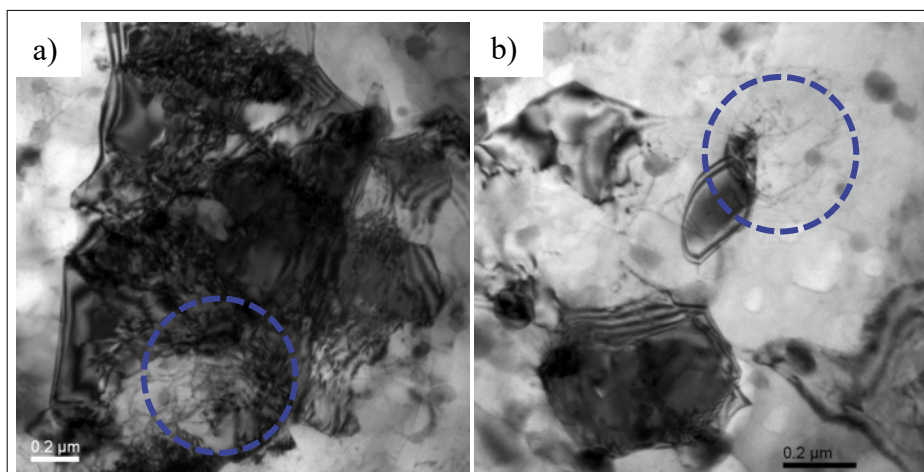


Fig. 8. (a) TEM micrograph of fourth pass sample after dynamic testing a) and b) perpendicular to applied stress direction, encircled area shows new recrystallized grains.

New dislocations were not formed and dislocations formed prior to dynamic loading might have undergone recovery, re-crystallization and grain growth process. Therefore, the stress waves in dynamic loading eliminate existing dislocations and increases the grain size of the material, which was obtained after ultra-fine grain processing. It is inferred that these applied stress waves induces the temperature which might attain re-crystallization temperature or above that temperature. The severity of the preferred grain orientation was also decreased as evident from electron diffraction pattern. Typical strain field contrast is evident as marked by an arrow in figure 9a.

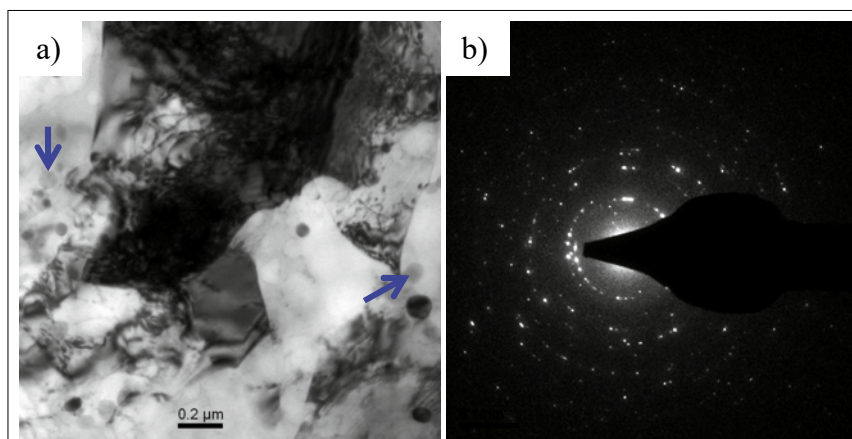


Fig. 9. (a) TEM micrograph of fourth pass sample after dynamic testing; b) selected area diffraction pattern of figure 8a in plane perpendicular to applied stress direction

The shear band deformation was not evidenced in aluminum alloys so far even at high rate of loading, due to ductile and deformation characteristics of the material in closely packed slip planes $\{111\}$ and slip directions $\langle 110 \rangle$. The barrier height for available dislocation decreases, which results in dislocation annihilation by dynamic recovery process and leads to dynamic re-crystallization, thus proving that the instability in the material directly depend upon adiabatic thermal effect on dislocations. For high ductile materials like aluminum, the flow stress will be discontinued due to absence of shear bands. The stacking fault energy of UFG Al-3%Mg alloy is very high and there were no deformation twins observed in the microstructure after dynamic testing. Even though pulse duration plays an important role in forming of twins or twin boundary, in 150μsec it is impossible to produce twins in aluminium

alloy material. However, steel can form twin structure even in 2μsec whereas it is ever impossible in aluminum alloys. This twin structure formation in steels is depending upon grain size of material. The annealed material deforms homogeneously without shear band formation and reveals absence of twin structure under high strain rate test conditions. The shock waves sometimes result in solidification especially for metals like aluminum and its alloys. The shock or impact pressure to attain the melting temperature is in the range of 102GPa to 105GPa for aluminium alloys. Since Al-3%Mg alloy reveals face centered cubic crystal structure with second phase particles, the phase transformation and hardening structure were absent in the tested material.

5. Conclusions

Based on investigation the conclusion shall be followed which listed as

- The dislocation density increases after each equi-channel angular pressing pass.
- The grain size decreases with increase in each pass of equi channel angular pressing is underlying strengthening mechanism for increase in strength of material.
- The slight increase in the grain size after dynamic testing shows structural in-stability of nano crystalline Al-3%Mg alloy.
- An increase in temperature of specimen due to adiabatic heating (during dynamic testing) plays a major role in recovery, dynamic re-crystallization and grain growth process of an ultra-fine grain alloy.
- Shear band deformation no longer exists in high ductile aluminum alloys.

Acknowledgements

The authors gratefully acknowledge phase stability lab and high speed mechanics lab, Indian Institute of Technology Kanpur, India for providing various facilities for producing Al-alloy samples via equi channel angular extrusion and conducting high strain rate testing on those specimens respectively.

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